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The Role of CCUS in Achieving Net Zero Emission

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1. Abstract

The burning of fossil fuels is a major cause of climate change, with the shipping sector contributing 2-3% of global carbon emissions, or 700-850 million tonnes of CO2 annually. One solution to this issue is Carbon Capture, Utilization, and Storage (CCUS), which can reduce emissions by 80-90%. CCUS also helps decarbonize hard-to-abate industries, provides lower-carbon energy, boosts energy security, and stimulates economic growth. The cost of capturing CO2 ranges from $15 to $120 per ton, depending on location and technology.
Floating Production Storage and Offloading (FPSO) vessels are key tools in offshore decarbonization. They collect, compress, and temporarily store CO2 emissions from offshore facilities. Specialized vessels then transport the liquefied CO2 for long-term geological sequestration. The combination of CCUS with FPSO technology significantly enhances emission reduction efforts and supports the transition to net-zero energy systems.

By helping reduce atmospheric carbon, these vessels play a vital role in achieving global decarbonization goals and advancing efforts to mitigate climate change.

2. Keywords
2.1 Carbon capture and storage (CCS),
2.2 Liquified CO2 transport,
2.3 Carbon sequestration,
2.4 CO2 shipping

3. Introduction

Climate change is a big problem that affects our planet in many ways, like rising temperatures, stronger storms, and rising sea levels. One of the biggest causes of climate change is the release of carbon dioxide (CO_2) into the air, mostly from burning fossil fuels like coal, oil, and natural gas. CO_2 is a greenhouse gas that traps heat in the atmosphere, causing global warming. To tackle climate change, we need to reduce the amount of CO_2 we release into the air. Carbon Capture, Utilization, and Storage (CCUS) is one way to do this. It involves three main steps: capturing CO_2 emissions from factories and power plants, using CO_2 in useful ways, and storing it safely underground.4. Objective

4.1. What is Carbon Capture, Utilization, and Storage (CCUS)?
4.2. Why is CCUS Important?

4.3. Benefits of CCUS
4.4. Challenges Facing CCUS
4.5. The Future of CCUS
5.Materials and Methods

Shipboard carbon capture involves running exhaust gas from a ship engine(s) and auxiliary power equipment through a CO2 capture system. Treated exhaust gas with a significant reduction of CO2 is discharged to the ambient atmosphere while captured CO2 is compressed, liquefied, and stored aboard (solvent, sorbent, and cryogenic technologies) or retained on the sorbent (calcium looping technology) until the captured CO2 can be unloaded when the ship docks.
A techno-economic analysis (TEA) for shipboard carbon capture was performed. The TEA assessed the technical and economic viability of shipboard post-combustion carbon capture and storage. This report summarizes the results of the techno-economic analysis. A techno-economic analysis is, as the name implies, a combination of a technical analysis of a process or technology followed by an economic analysis. The technical analysis for this study included such things as quantifying utility requirements (shaft power, heat, water, etc.) as well as quantities, weights, and volumes of feedstocks, process products, and consumables. The technical analysis was followed by an economic analysis where capital, operating and maintenance costs were estimated.
A block flow diagram of the system to be analyzed is shown in Figure I. Exhaust gas from the ship engine(s) and auxiliary power equipment is treated in the CO2 capture system. Treated exhaust gas with a significant reduction of CO2 is discharged to the ambient atmosphere. Captured CO2 is compressed, liquefied, and stored aboard ship until it can be unloaded when the ship docks.
(Refer to Figure I)

5.1 Explanation of components of Block Diagram

5.1.1. Exhaust CO_2 Capture

Exhaust CO_2 capture on ships involves removing carbon dioxide from engine emissions before it is released into the atmosphere. This process typically uses post-combustion capture methods, such as amine-based chemical absorption, membrane separation, or solid sorbents. The exhaust gases pass through a scrubber or absorption unit where CO_2 is selectively captured, while other gases like nitrogen and oxygen are released. This technology helps reduce a ship's carbon footprint and comply with international regulations like the IMO's greenhouse gas reduction targets.

5.1.2. CO_2 Compression

Once the CO_2 is captured, it needs to be compressed to facilitate storage or transportation. Compression reduces the gas volume significantly, making it easier to handle onboard. The captured CO_2 is pressurized in multiple stages using compressors, with intercooling to manage temperature rise. The typical pressure range for shipboard compression is around 6 to 8 bars for transport or higher for liquefaction. Efficient compression is essential to minimize energy consumption and ensure smooth integration into the ship's existing power and propulsion systems.

5.1.3. CO_2 Liquefaction

After compression, the CO_2 is cooled further to convert it into a liquid state for efficient storage. Liquefaction occurs by cooling the compressed CO_2 to temperatures below -50°C, using refrigeration cycles such as ammonia or CO_2-based cooling systems. The liquefied CO_2 has a much lower volume than its gaseous form, allowing for compact storage in specially designed cryogenic tanks. Maintaining stable temperatures and pressures is critical to preventing phase changes that could disrupt storage and handling.

5.1.4. CO_2 Storage

The final step is the safe storage of liquefied CO_2 onboard until it can be offloaded at a port for further processing or sequestration. Dedicated insulated storage tanks with pressure and temperature controls are used to maintain the liquid state. The stored CO_2 is either sent to shore facilities for industrial reuse, geological sequestration, or potential onboard conversion using emerging carbon utilization technologies. Proper monitoring and leak prevention measures are crucial to ensuring safe operations and regulatory compliance.

5.2 Carbon Capture Technologies

5.2.1 Cryogenic

The A3C technology is based on the proven concept of separating carbon dioxide by freezing it out of a gas mixture. In a typical implementation, the separation process follows a gas pre-treatment step which removes water and contaminants from the exhaust gases. The separation stage produces a stream of carbon dioxide gas which is liquefied by the conventional compression and cooling steps. The liquid carbon dioxide is then stored in insulated tanks. The first stage of the process is a conventional scrubber that washes traces of soot and soluble acid gases, such as Sulphur dioxide, from the exhaust gas. This stage may use an open or closed water cycle to wash and cool the gases. The wash water is treated to remove any suspended contaminants with dosing as necessary. The second stage, which may form part of the first column, is a cooled quench section using circulation of chilled water. This stage cools and reduces the water vapour content of the gases to very low levels. Any residual soot or soluble contaminating gases are further reduced in this stage. The final step in the pretreatment is the cooler-drier moving bed heat exchanger. This heat exchanger uses the cold low carbon dioxide content exhaust gases from the separation stage to cool the cleaned inlet gases using an intermediate bed of fine metallic or ceramic beads. The remaining small amount of water vapours in the inlet gases is condensed or frosted onto the bed material and evaporated into the lean exhaust gas stream. The inlet gases leave this stage at around -100°C (-148°F). The separation process uses a further moving bed heat exchanger to cool the cold inlet gases so that most of their carbon dioxide content is deposited as a frost on the circulating metallic or ceramic beads. The beads move slowly counter to the inlet gases and once they pass out of the contact region, they are warmed sufficiently to sublime the carbon dioxide frost off the bed at around -75°C (-100°F). The warmer bed material is elevated to the top of the heat exchanger where it is cooled to the inlet condition over refrigerated heat exchange surfaces. This temperature is as low as necessary (typically -125°C, -195°F) to reduce the carbon dioxide concentration in the outlet gases to less than 10% of the level at the inlet. The cold low carbon dioxide gases leave the separation stage for energy recovery in the cooler-drier. Despite the pre-treatment stages there will remain low levels of trace contaminants such as unburned hydrocarbons, nitric oxide and carbon monoxide. However, these gases have too low a vapour pressure to condense in the range of temperatures in the separation stage and pass through the capture process unchanged to be discharged to atmosphere. The cooling necessary for the process is provided by a nitrogen cycle refrigeration system. This technology is conventional e.g., for boil off gas re-liquefaction on liquefied natural gas (LNG)

carriers. In the A3C application conditions are less demanding and by rejecting heat at low temperatures to warm the packed bed to recover the carbon dioxide, the compressor energy consumption is radically reduced. This close integration of refrigeration reduces the energy consumption of the process to less than 33% of the amine process, to well below 1GJ/ton compared with around 3 GJ/ton.
(Refer to Figure II)

5.2.2 Calcium Looping

5.2.2.1 Introduction to Seabound

Seabound is a climate technology startup on a mission to decarbonize shipping. Seabound is developing ship-based carbon capture equipment to reduce up to 95% of CO2 emissions from existing or newbuild vessels. Founded in Oct 2021, Seabound has so far completed a successful sea trial of a pilot system to capture CO2 at 1 tons/day on a 3200 TEU container vessel, signed 6 letters of intent with major shipowners to purchase early systems, and secured backing from leading investors including Y Combinator, Lower carbon Capital, and Eastern Pacific Shipping Ventures. Sea bound's ambition is to install carbon capture equipment onboard 1,000 vessels by 2030 and 10,000+ vessels by 2040 to capture 100M+ tons of CO2 per year by 2040.

5.2.2.2. Technology Overview

Seabound is developing a decoupled onboard and onshore approach to carbon capture that leverages calcium looping technology. Calcium looping is a cyclical, two-step process between carbonation and calcination. First, lime in pebble form is loaded onto a vessel that has an installed Seabound carbonator. In the carbonation step, the exhaust gas is routed through the carbonator in which its constituent CO2 reacts with and binds to CaO contained within the reactor to form calcium carbonate (CaCO3). The CaCO3 is then ejected from the reactor and temporarily stored onboard the vessel until it reaches port for off-loading and post-processing. The second calcination step occurs on land, if at all: CaCO3 is heated in a zero-emissions lime calciner to regenerate the CaO and separate it from CO2. The CaO can be re-loaded onto another vessel with a carbon capture system and the CO2 sold as a feedstock for new products (e.g. synthetic fuels, chemicals) or transported for geological sequestration. Alternatively, the CaCO3 can be sold directly as a feedstock to the lime or construction industries. (Refer to Figure III)

5.2.2.3 The use of calcium looping for ship-based carbon capture has multiple advantages:

1. Lowered CAPEX compared to conventional carbon capture technologies (e.g. amines): Calcium looping enables the decoupled process of carbonation and calcination to take place on ships and on land respectively, which reduces onboard equipment size and CAPEX, reduces the total number of calciners required and moves the energy-intensive calcination step to land.

2. Negligible energy consumption for the capture process onboard: The carbonation reaction is exothermic - it releases rather than consumes energy, which has the potential for waste heat recovery to reduce additional fuel consumption.

3. Minimal operational complexity: CO2 is stored in the stable, solid form of CaCO3 (i.e. limestone) for easy handling, eliminating the need for CO2 compression/liquefaction and refrigerated/pressurized tanks onboard.
4. No toxic chemicals: CaO and CaCO3 are non-toxic materials that are safe for both the environment and crewmembers.

5. Potential for ocean CO2 removal: longer-term, CaCO3 and residual CaO could potentially be discharged directly overboard to support ocean alkalinity enhancement (pending further environmental studies and regulatory approval).

5.2.3 Solvent

Solvent gas separation technologies are common in the process industry and all have similar flow diagrams. Figure 8 shows a flow diagram for the solvent system planned by Stena Bulk for the SuezMax.7 Exhaust gas from the main engine, generator, and boiler will enter the capture system flowing through a Waste Heat Recovery Unit (WHRU) and then into a Quench unit for further cooling and removal of SO2 and NOx. Cooled exhaust gas will then enter the suction of a booster blower to provide pressure to push the exhaust gas through the Absorber and Water Wash. The solvent absorbs CO2 from the exhaust gas in the Absorber. The Water Wash is necessary to scrub the exhaust gas of any solvent aerosol carryover. Solvents are generally toxic materials and it is essential to limit emission of solvent materials. CO2 is absorbed by the solvent in the Absorber vessel. Rich solvent (solvent containing CO2) flows out of the bottom of the Absorber and is pumped through a rich solvent-to-lean solvent (low CO2 concentration) heat exchanger where the rich solvent is preheated and the lean solvent cooled. The pre-heated rich solvent enters the top of the Stripper where it is heated with heat introduced into the Reboiler. CO2 is driven from the solvent and exits the top of the Stripper along with a significant amount of water vapor. CO2 exiting the Stripper is cooled removing most of the water vapor

and then flows to compression, drying, liquefaction, and storage. Lean solvent exiting the bottom of the Stripper flows to the Main-HEX and then is pumped to the top of the Absorber, thereby completing the solvent cycle. Current research for solvent systems focuses on solvent development with efforts to reduce corrosivity, toxicity, and regeneration auxiliary requirements. The Stena Bulk analysis is based on monoethanolamide (MEA) as the solvent. MEA is a mature solvent that was developed many decades ago. Stena Bulk indicates that 53% more fuel is required to provide auxiliary power for a 90% capture system that also captures CO2 from the auxiliary power exhaust gas. Based on this current study and reverse engineering, shaft power of 0.0213 kW/pph of CO2 captured and thermal input of 1,500 Btu/lbCO2 is required. In the NETL study, it is indicated that the Can Solv solvent only requires 1,050 Btu/lbCO2. 8 This TEA analysis uses the 1,050 Btu/lbCO2 value which results in about 40% more fuel consumption instead of 53% more.
(Refer to Figure IV - CO2 capture system by solvent method in detailed)

5.2.4 Adsorbents

Exhaust gas from the ships engines, generator, and boiler will enter the capture system at stream 1 and be boosted in pressure. The major components of the system include the dehydration and SO2 removal system (2 vessels on the upper left) and CO2 removal system (3 vessels on the upper right). Exhaust gas enters stream 1 and flows first through the dehydration system from stream 14, to the CO2 removal system through stream 21, and out of the CO2 removal system through stream 23 to the second bed of the dehydration system where it is used to regenerate the dehydration sorbent. The exhaust gas cleaned of CO2 and SO2 exits the dehydration system through stream 5. CO2 products are removed from the CO2 Adsorbers through stream 29 and through the 2-stage vacuum pump system. From the surge tank, CO2 will be introduced to the CO2 compression and liquefaction system for the shipboard capture application. The balance of the system provides heating and cooling to assist in the regeneration of the dehydration and CO2 removal sorbents. (Refer to Figure V)

5.2.5. Membranes

Information for a membrane system was requested from a membrane developer that is very prominent in CO2 capture from stationary power generation. After a few communications regarding this application, it was concluded that a membrane is not a good technology because of the low CO2 concentration in the exhaust gas (4 – 8%) and the high capture stipulation (90%). As a result of these communications, it was decided not to include a membrane case.

6. Results and Discussions

(Refer to Figure- VI, VII & VIII)
Carbon Capture, Utilization, and Storage (CCUS) using the solvent method in ships offers several benefits and advantages, particularly in the maritime industry's efforts to reduce greenhouse gas (GHG) emissions.

6.1 Benefits and Advantages of CCUS Using Solvent Method in Ships

6.1.1 Significant CO_2 Reduction

The solvent method effectively captures CO_2 emissions from ship exhaust gases, helping ship operators comply with stricter emissions regulations like the IMO's decarbonization targets.
Can reduce onboard CO_2 emissions by up to 90%, depending on the solvent type and system efficiency.

6.1.2 Compliance with Environmental Regulations

Helps meet the International Maritime Organization (IMO) 2050 target of reducing total GHG emissions from ships by at least 50% compared to 2008 levels.
Supports compliance with the EU Emissions Trading System (ETS) and other regional carbon pricing mechanisms.

6.1.3 Fuel Flexibility

Works well with conventional fossil fuels like HFO, VLSFO, and LNG, allowing shipowners to continue using existing fuel infrastructure while reducing emissions.
Can be integrated into future low-carbon fuel systems (e.g., ammonia, methanol) for additional environmental benefits.

6.1.4 Potential for CO_2 Utilization

Captured CO_2 can be stored onboard and later used for enhanced oil recovery (EOR), algae-based biofuel production, or synthetic fuel synthesis. Can be sold or transferred to shore-based facilities for utilization, creating economic opportunities.

6.1.5 Energy Efficiency & Scalability

Amine-based solvents (e.g., MEA, MDEA) are highly efficient in absorbing CO_2 and can be regenerated for continuous use. Modular and scalable technology can be installed on different vessel sizes, from small cargo ships to large tankers.

6.1.6 Compatibility with Existing Ship Designs

The system can be retrofitted onto existing ships, reducing the need for complete vessel redesigns. Can be integrated with exhaust gas scrubbers to enhance emissions control.

6.1.7 Reduction in Carbon Tax & Emission Penalties

Reducing onboard CO_2 emissions can lower exposure to carbon taxes and penalties imposed by governments and regulatory bodies. Can improve a ship's Carbon Intensity Indicator (CII) rating, reducing long-term operational costs.

6.1.8 Improved Corporate Image & Marketability

Shipping companies that adopt CCUS can enhance their reputation as environmentally responsible operators, attracting eco-conscious customers and investors. Helps companies meet Environmental, Social, and Governance (ESG) goals.

6.2 Costing

(Refer to Table I)

It is estimated that shipboard CO2 capture and storage can be performed for a cost ranging from approximately \$150 to 200/tons CO2 captured depending on the ship and the capture technology. The Cost of CO2 Avoided is higher, ranging from approximately \$175 to \$250/tons CO2 avoided, depending on the technology selected.

Installed capital cost is estimated by multiplying the equipment cost by a Lang factor. Equipment cost scaling for capacity was performed using the conventional equation:

Cost=CostrefX(Capacity/Capacityref)n

Where:

Capacity – process capacity of interest, e.g. this could be the CO2 capture rate or exhaust gas flow rate
Capacity ref – process capacity at reference conditions
Cost – Equipment cost at the new capacity
Cost ref – Equipment cost at the reference capacity
n – scaling exponent (value of 0.7 was used)

The capture system cost will increase as the exhaust gas and CO2 capture rate increase due to the need to provide auxiliary power.

7. Conclusion

The process appears to be technically feasible with no major barriers emerging during the course of the study. Optimization of the engine and/or waste heat recovery units to be more compatible with a carbon capture system may reduce the need for additional fuel consumption. Vessels using engines with more waste heat availability may prove more feasible with the system as designed. As the marine industry sets course for 2030 with an ambition to meet the IMO targets for greenhouse gas emissions, other carbon reduction technologies are likely to remain more attractive. By 2030 more mature networks and infrastructure to process and sequester large volumes of carbon dioxide are expected to be in place. Utilizing those systems for the off-loading of carbon dioxide captured on ships may prove attractive. Regardless, if the costs of marine carbon capture can be sufficiently addressed, it could play an important role in a multi-pronged effort to meet the challenge of decarbonizing the marine industry.

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10. Figures

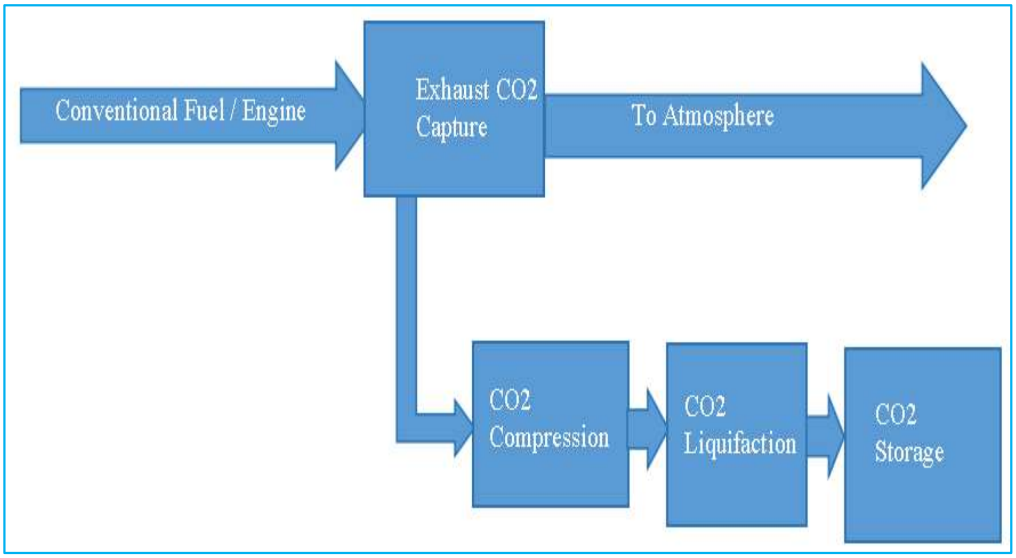

Figure I – Flowchart / Block Diagram of Carbon Capture System

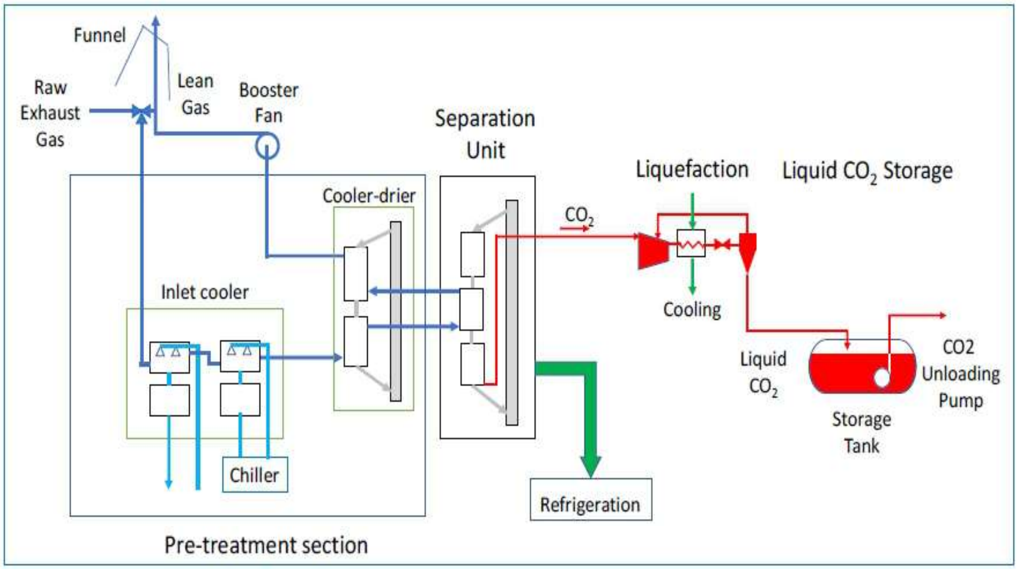

Figure II – Cryogenic Method of Carbon Capturing

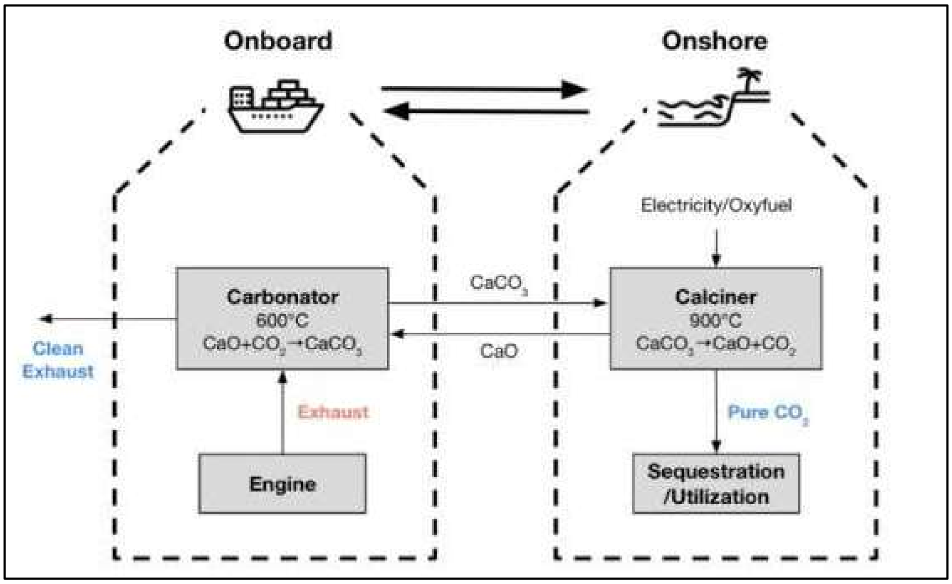

Figure III – Calcium Looping Method of Carbon Capturing

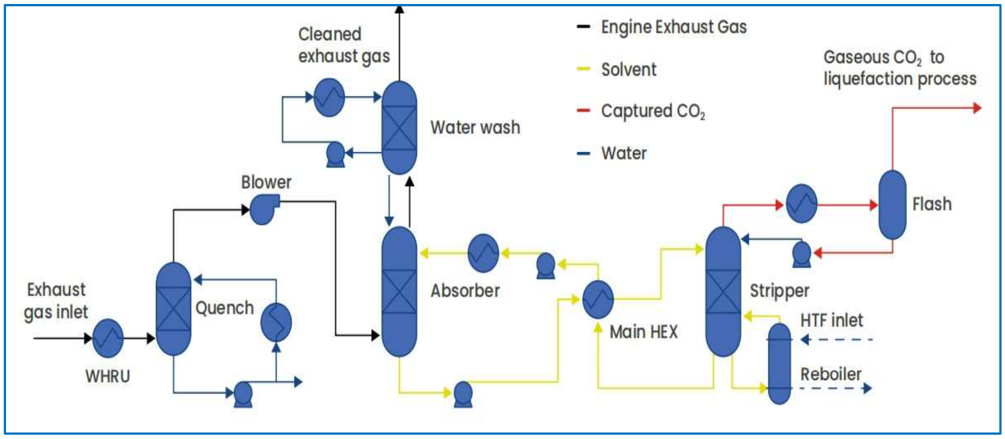

Figure IV – Solvent Method of Carbon Capturing

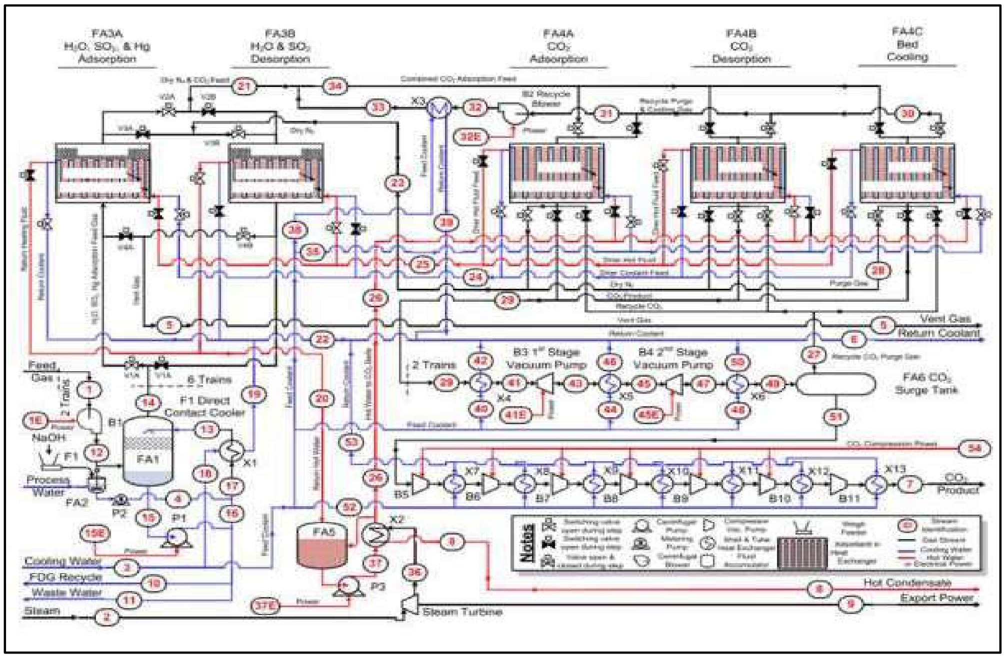

Figure V – Adsorbents Method of Carbon Capturing

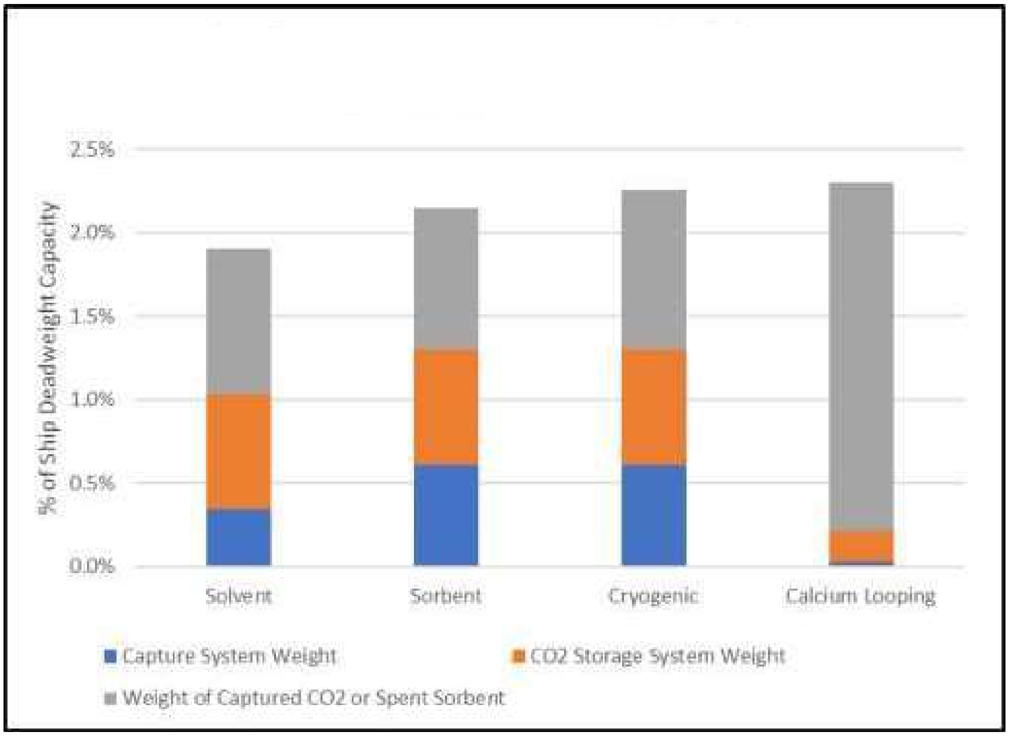

Figure VI – Comparison of Weight of Capture, Compression, and Filled Storage Systems by different methods for vessel Map Runner

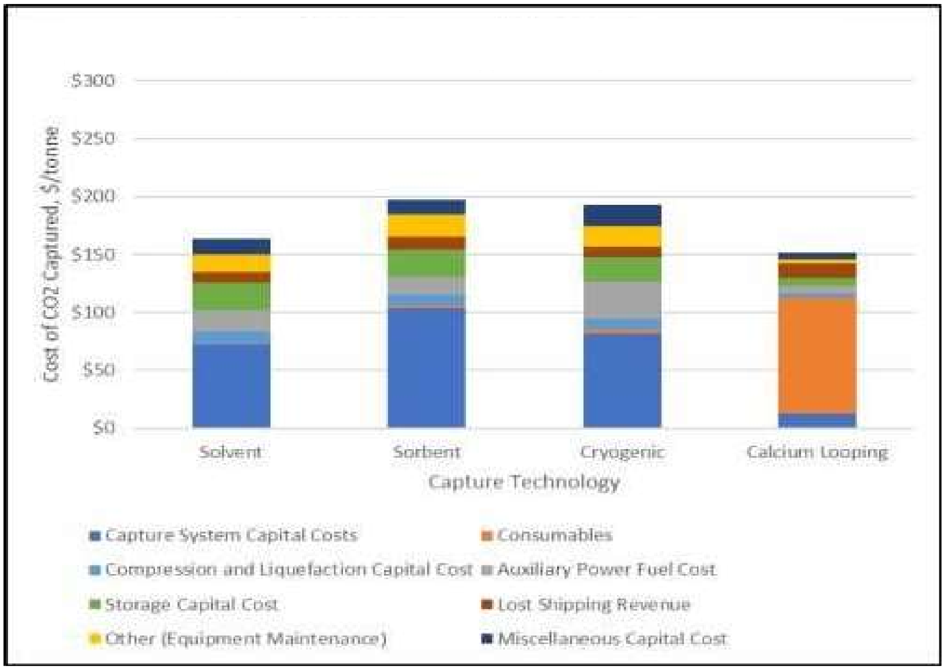

Figure VII – Comparison of Cost of CO2 Captured by different methods for vessel Map Runner

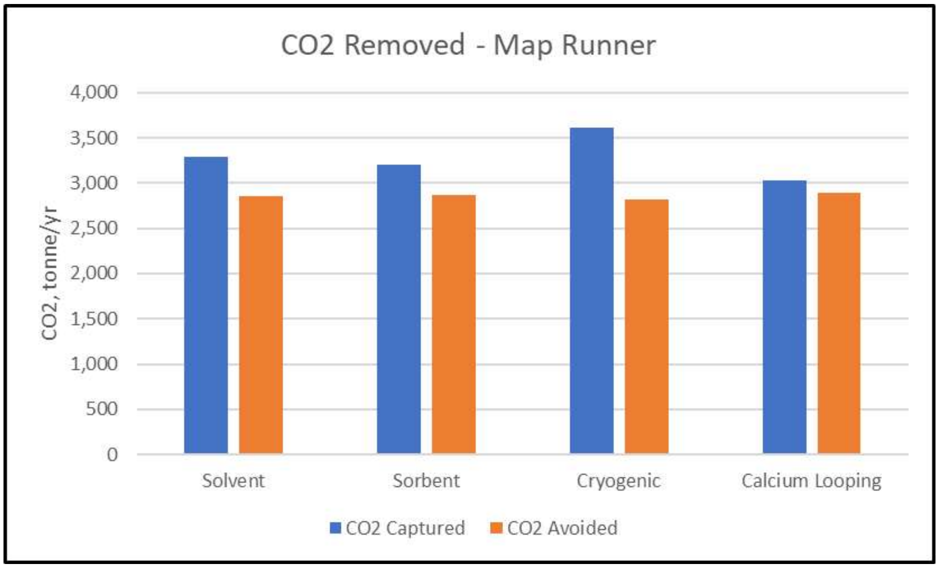

Figure VIII- Comparison of CO2 removed by different methods for vessel Map Runner

11. Tables

Table I – Running costs and returns if aiming for a 25-30% avoidance rate to meet IMO'S 2030 target

	If capture system is always used when sailing	If used 50% of the time when sailing	50% usage unti 2025, increasing to 100% by 2030
Total CO2 (MT/Y)			
CO2 produced	35,540	35,540	35,540
Emitted / Vented	24,891	30,216	28,299
Captured	10,649	5,325	7,241
% Captured (avg Over lifetime)	30%	15%	20%
Total investmen over lifetime (12 years)	**$18.5m**	**$17m**	**$17.6m**

Changes to running costs ($/D)			
Total extra running cost	4,727	4,151	4,358
-Of which due to fixed costs	4,232	3,903	4,022
-Of which due to variable costs	495	248	337
Of which due to sequestration	438	219	298
$/tCO2	**175**	**297**	**232**

Over 20 years lifetime			
Total extra running costs $/D	4,101	3,524	3,732
$/tCO2	**153**	**254**	**201**

Over 20 years with a subsidy of $35/TCO2			
Total extra running costs $/D	3,080	3,014	3,038
$/tCO2	**106**	**207**	**153**